Control Scheme for Energy Storage in Domestic Households

Qingqing Yang
University of Bath
qy256@bath.ac.uk

Chenghong Gu
University of Bath
C.Gu@bath.ac.uk

Simon Le Blond
University of Bath
S.P.leBlond@bath.ac.uk

Jianwei Li
University of Bath
jl977@bath.ac.uk

***Abstract*-Distributed solar photovoltaic panels (PV) installed on the roofs of domestic houses generate electricity from sunlight, which is important for both decarbonization and electricity bill reduction. This paper proposes a new control approach to enable high density solar PV generation to be connected to low voltage (LV) networks more efficiently by working closely with in-home battery. The charging and discharging periods are crucially important for improving the efficiency of the PV battery. An optimal control scheme for energy storage systems in LV networks is introduced to facilitate demand response (DR). The method described also regulates thermal violation and voltage violation caused by PV generation. Finally, the paper uses a five node LV network and typical household profiles to demonstrate the effectiveness of the proposed control strategy. The benefits in terms of load shift are shown under three different configurations by using a selected lithium-ion battery.**

***Index Terms*--Solar PV, LV distributed network, energy storage, power flow.**

I. INTRODUCTION

With the accelerated increase of energy demand, the traditional fossil energy supply is close to the limit and the resulting energy crisis will adversely affect people's lives [1, 2]. People are seeking more approaches to mitigate or solve the energy crisis, and some of them try to use the more efficient conventional fossil fuels methods or utilize alternative energy sources (i.e. clean renewable energy). Solar energy is the most basic forms of energy in survival and development of a variety of organisms including humans. However, solar energy intermittency may cause power quality and generation and load mismatch issues. If solar energy couples with efficient battery storage devices, the network will be tremendously improved.

The joint module contains distributed generation and battery storage that can be operated in stand-alone or grid-connected modes, comprising a tiny electrical power system. Its value is that it can overcome the negative influence of distributed power generation to the grid, minimize transmission loss and provide reliable power according to the needs of customers.

The key of making full use of renewable energy is to improve the highly efficient energy storage device and its corollary equipment. They could match the PV power generation, support the fast switch of charging and discharging status and ensure the safety and stability of the whole system. In allusion to the solar home systems in LV network, the battery system is chosen in this paper. A methodology based on demand signal is developed for demand response in typical households' energy management system. Eventually the battery charging and discharging method is tested on a five bus model.

II. TECHNICAL ISSUES ASSOCIATE WITH GRID-CONNECTED PV SYSTEMS

Considering the feed-in tariffs currently available from the UK government, the grid-connected PV power generation systems are the best choice for general residents. However, there is an obvious volatility in PV system that the characteristics of solar energy could not be anticipated because of the natural conditions [3].

The junction power from PV cells increase as light intensity increase. Typical peak time of output is noon when the sun irradiance is high. However, the load demand at this time is relatively low for household.

The typical load profile of a household integrated with PV output is plotted in Fig.1. The winter scenario is selected in this paper and the data is collected from 'Load Profiles and Their Use in Electricity Settlement' of Elexon [4].

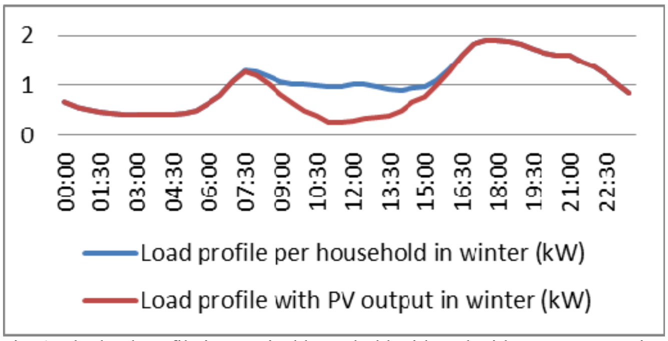

Fig. 1. the load profile in a typical household with and without PV output in winter.

In winter, following the daily load profile in a typical household in UK, there are two obvious peaks in the curve and two obvious valleys as well. The peak demand may bring enormous congestion to the grid. After connecting PV systems, both the load distribution of the entire distribution network and the power flow of the system will change. The PV distributed generation will bring a lot of benefits in energy saving, but also adverse impact the system, such as a sharp gap in load demand. In order to enable demand response to enhance the positive effects in distribution

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systems, the peak load should be shifted to a relatively low-load period of the day.

From previous studies, the main positive effects on grid-connected PV systems are to reduce the power loss and compensate voltage change. Grid-connected PV generation system does not have the capability for peak regulation and frequency modulation.

When distributed generation is connected to the network, the major impacts to the voltage of system are manifested in two ways. When distributed generation operation is coordinated with the local load it will suppress voltage fluctuations. The power output of distributed generation changes along with the load profiles in the same direction. On the other hand, the distributed generation cannot always operate with the local load in a coordinated way. The voltage fluctuations of the system will increase at this time. Due to the principle of wave propagation, the closer to the load the greater the voltage fluctuation [5]. Particularly, overvoltage, which could happen in LV network with solar PV generation, may cause tripping of other equipment.

Therefore, it is of great importance to improve randomness and disaggregate the power output of local photovoltaic power generation.

III. Battery Charging And Discharging Theory

The battery storage system is like a bank to store the extra electricity generated in the trough demand period, and relieve the tension of peak demand. The waste of electrical energy and the line losses of the system will both be reduced. In this way, the line and devices will have longer lifespan. Coordinating energy storage systems with distributed generation, the energy storage devices are utilized to compensate and reduce the randomness of power output, and also improve the stability of grid. By correctly incentivizing customers, Distribution Network Operators (DNOs) should be better able to facilitate different demands. The benefits will be maximized by using energy storage system on LV networks.

Lithium-ion battery, abbreviated as li-ion battery, has seen rapid development over a number of applications. In this study, the li-ion battery is chosen because of its advantages in the combination of performance capability, safety, lifespan and costs over other types of batteries, although lead-acid battery is a more mature technology [6]. Compared with other types of battery used in battery storage for PV systems, the charge and discharge curve of li-ion battery is nearly flat, and this means less voltage variation will appear in the system [7]. The power demand and battery state-of-charge profiles with time varies are shown in Fig. 2.

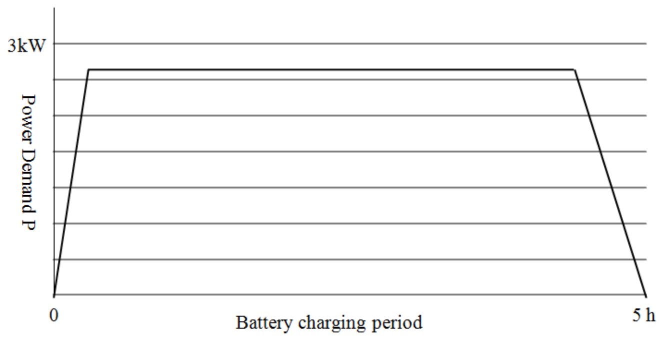

Fig. 2. Charging profile of the lithium-ion battery [8].

To prevent the battery from over charging, two control methods for charging and discharging are proposed. A cut-off voltage will efficiently avoid over charging, i.e. the working voltage should be under the specified voltage [9]. If the specified voltage is exceeded, the controller will either disconnect the PV panel and the load or initiate PWM pulse current charging. The other method is to control charging and discharging based on SOC of battery, which is more secure and reliable. If SOC is low, the controller will conduct equalizing charge to reduce harm to the battery in underfilling state. Similarly, the charging will stop if SOC is high. In order to satisfy the requirement of better performance for large PV farms, usually the second method is chosen. Depth of discharging will directly influence the service life of the battery, limiting the occasions of application with random charging source. Nonetheless, the overcharge protection circuit or balance circuit could improve the batteries' security and lifespan.

IV. Battery Charging and Discharging Design

The key function of battery is to store the energy generated from PV system and provide energy when the load demand is high or other generating sources are unavailable. In the system, the flow chart for the working principle of the battery system is designed in Fig. 3. Through an appropriate battery control strategy, the thermal violation and voltage violation will both be effectively controlled.

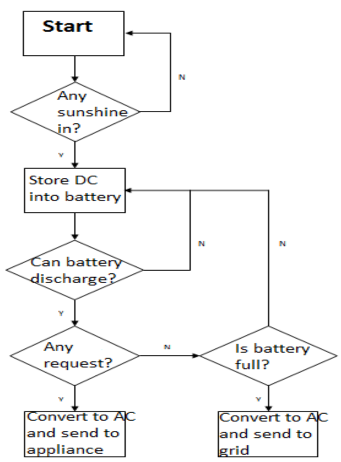

Fig. 3. Flow chart for working principle of battery system.

In this system, the charging and discharging cycles will repeat in battery system continually. However, the charging and discharging behaviour should be controlled in a suitable manner to keep the battery in a satisfactory condition and extend its lifespan [10]. The flowchart of designed energy storage charging and discharging cycle is represented in Fig. 4.

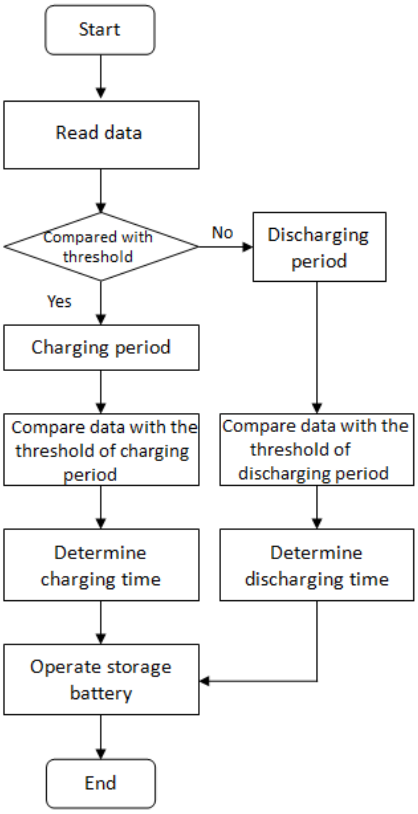

Fig. 4. Flowchart of energy storage charging and discharging cycle design.

The original load profile and the threshold will be gotten. State of Charge can be determined by the previous charging and discharging state, the charging and discharging current and the duration between the two charging periods. The SOC could be obtained as below (1) [11]:

$$SOC\left(t+\Delta t\right)=SOC\left(t\right)+I\Delta t \quad (1)$$

Based on the original load profile, the new data can be obtained from equation (2):

$$L_{new}=L_{original}+VI_{ch}T_{ch}-VI_{disch}T_{disch} \quad (2)$$

In this equation, L_{new} is the new load profile obtained, $L_{original}$ stands for the original load profile, V is the voltage in the battery, I_{ch} and I_{disch} are the charging and discharging current respectively. T_{ch} and T_{disch} are the charging and discharging time.

The capacity of energy storage is conducted by the controller which could reduce peak demand to mitigate congestion in the network. According to the capacity of transformers and circuits, the network cost of investment and other factors, threshold in terms of the load demand and the network conditions could be determined. At the peak period, the maximum load demand should require reinforcing the network with the amount of customers and coincidence factor divided into thermal violation and voltage violation. If not, at the trough time, the given 90% level of peak situation (i.e. 0.9 times thermal violation and voltage violation divided by the amount of customers and coincidence factor) will be used to calculate the threshold. The threshold is supposed to be the load demand of the household, and it is an overriding value as a standard to distinguish the charging and discharging periods.

The duration T is defined according to the demand of the customer. In the charging period, the load demand should be low and the PV generation is high. If the load demand is relatively high and there is little PV output, these characteristics are suitable for a discharging period. Namely, if $L_{original}$ is larger than the threshold, the period is selected as charging period. If not, when $L_{original}$ is smaller than the threshold, it will be the discharging period candidate. In order to obtain the specified charging period, the load demand on each time will be compared with the average load demand got from candidate period. Once the load reaches the specified value, charging or discharging will start.

V. RESULT

In this section, simulation based on the designed five nodes LV network is carried out and related analysis is studied. The solution of power flow analysis obtains power flow results include voltages at all the buses and line flows include power flows and losses in each lines specifically.

A. Test network

Based on theory, a five buses network is used to demonstrate the impact to the network and qualify the benefits in the system. In Fig. 5, a radial LV network model with low utilization is built in the Simulink platform created by PSAT. The cable data and substation data are shown in TABLE I. Data is based on a 3.5 kWp PV system from EcoHome Export Data of Western Power Distribution in Bristol [12].

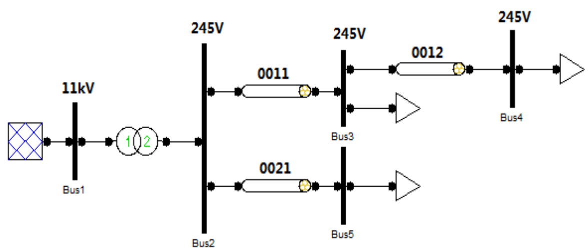

Fig. 5 Layout of a LV network.

TABLE I
SUBSTATION DATA [12]

Voltage (V)	Transformer Capacity (kVA)	Number of Customers per feeder section	MD Day	MD Night
11000 / 245	500	Feeder0011 – 118 121m	363k VA	163k VA
		Feeder 0012 – 18 88m		
		Feeder 0021 – 121 132m		

This network is designed for typical households in UK in LV distributed network with five buses. Through the transformer with 11 000 / 245 ratios, the power transmitted to the three feeders in radial LV network.

B. Parameters of Battery

Equipping energy storage devices could overcome the traditional shortcomings of small inertia in distributed generation. Also when the distributed generation is operating in either stand-alone mode or grid-connected mode, an appropriate battery size for a generic household demand should be selected.

The battery is a typical household energy storage system designed for the energy application by using both solar and grid input. The selected li-ion battery with 1500W output power and 2.4kWh capacity can fulfill the basic energy demand for most homes. The battery pack has been chosen is consist of 4□100Ah 12V DC battery cells which are connected to a nominal 24V DC system to form household energy storage [6, 13].

C. Result

Based on the battery charging and discharging theory, a threshold needs to be determined to decide the candidates for charging and discharging periods. The threshold is 0.9128 KW per household in winter. Hence, the selection of charging and discharging period is presented in Fig. 6.

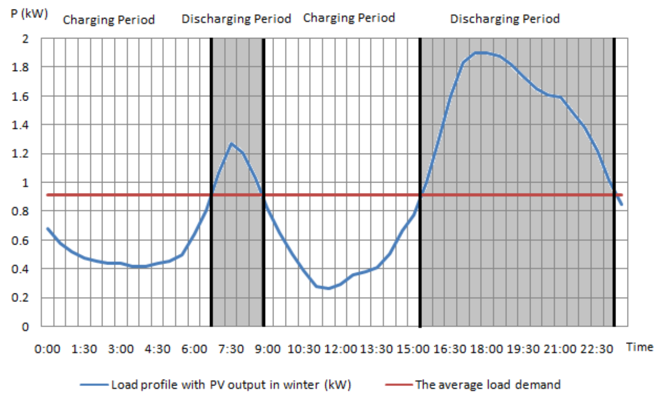

Fig. 6 the selection of charging and discharging period.

The period for which the load demand is over this threshold could be introduced as the discharging period and conversely, when the load demand is lower than the average value, the period could be chosen as charging period. In this system, the discharging candidate in the first peak is less than the discharging time. Hence, the period next to these points could be considered. The other period selection could be briefly chosen as the lowest points and highest points.

Based on the theory of battery charging and discharging design introduced and the charging / discharging candidates selected above, the charging and discharging period of this specified system is designed as follow: the charging period is from 2:30 to 5:00 and from 11:00 to 13:30; the discharging period is from 7:00 to 9:30 and from 17:00 to 19:00.

According to the parameter of the chosen battery, the duration of battery charging and discharging is about 2.5 hours, and hence the suitable period is selected among all the candidates. Compared with other works for selecting charging / discharging period, this paper is mainly focused on load shifting to balance the demand for each household. In this way, the battery could use electricity troughs to charge and fill the gap between troughs and peaks. The pressure on the grid caused by peak demand will be eased.

The power flow for general network and the network with battery charging / discharging behaviour is calculated. With the charging and discharging strategy designed above, the load profile has changed in Fig. 7.

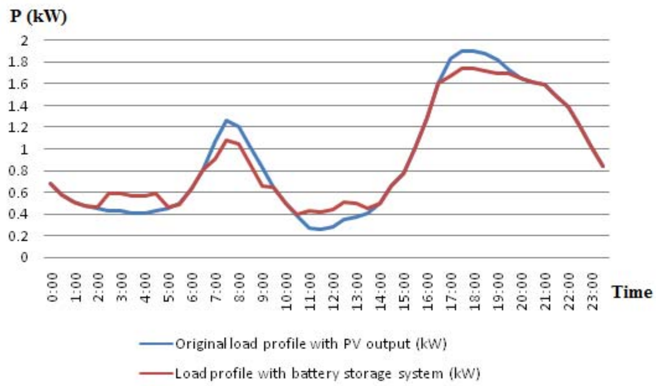

Fig. 7 Load profile under battery storage system.

Although the demand will increase during the charging periods, the peak demand is obviously decreased in the discharging period. With battery storage system, the peak demand could be reduced from 1.9kW to 1.7kW. The curve becomes a little flat, with smaller difference between the peak and trough. It is obvious that the two lines overlap during some periods but deviate in other periods.

The functions of energy storage system are to smooth the fluctuant output of PVs and improve the reliability of power supply. Hence, the fluctuations will be inhibited fewer than 10%, and the optimum value of power distribution should be controlled between 15% ~ 20%.

VI. RESULT ANALYSIS AND BENEFIT QUALIFICATION

The impact of battery storage on LV distributed network will be demonstrated in terms of load profile and power flow analysis, and the charging and discharging methods will also be testified based on voltage violation and thermal violation.

A. Voltage

From the demonstration, the use of the battery system could efficiently reduce the peak demand and increase the lowest demand. Hence, the network condition will improve mainly expressed by voltage improvement and network loss reduction. If the voltage is much higher or lower than the nominal value, it will cause damage to the power system. For the LV distribution network, when current through any electric device there will be a voltage drop between its terminals. With the optimal control scheme of the battery system, a large number of benefits will be brought in the network. The voltage drop is calculated as:

$$d_V = \frac{\left(V_{pre} - V_{post}\right)}{V_{pre}} \tag{3}$$

The voltage range is considered to be acceptable from -5% to +10% of the nominal value. If the voltage of the feeder is beyond this range, the network needs to be strengthened.

Based on the model, real time simulation (power flow) has been carried out to determine voltage at each busbar. The battery system is used to refine the voltage fluctuation of the low voltage network. Real time simulation has been measured at bus 2. Three cases are shown in Fig. 8:

- Case 1: the original LV network (the blue trace);
- Case 2: LV network with PV generation (the green trace);
- Case 3: LV network with both PV generation and energy storage (the red trace).

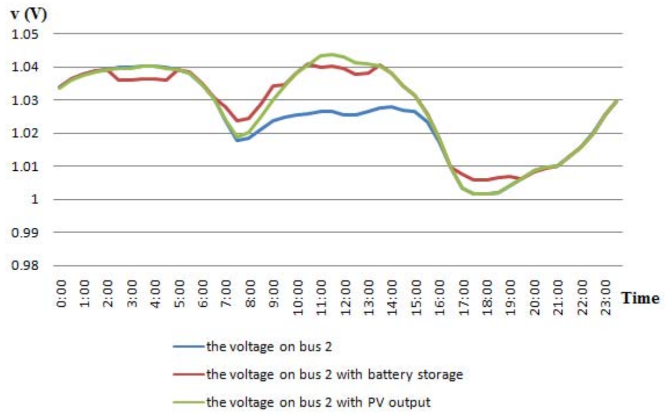

Fig. 8 the voltage on bus 2 with and without battery storage

Two obvious voltage drops can be observed. Clearly, the consumption of power is largest at these throughout the day. In addition, as described above, the closer to the load side, the more obvious the voltage fluctuation. Hence, the most severe voltage violation can be observed at busbar 4 compared with other busbar which is around 6% which is reasonable for the operation of power system. In the distributed network, the voltage is different from the bus next to it since the farthest bus will have the lowest voltage drop. The dissimilarity of voltage from different situations is caused by the load demand variation. The peak demand will bring the heaviest voltage drop. When the PV generations are applied in the LV network, a slight rise of voltage can be observed during daytime but only when there is enough sunlight for the PV panel. Therefore, the PV system causes two kinds of differences: on the one hand the voltage drops are decreased and on the other hand the voltage fluctuation may be greater.

By adding PV generation system, the gap between troughs and peaks will increase by 12.8%. In addition, the voltage will increase around 7% at the peak time. The line loss could be reduced 6% and the capacity will decrease 10% at the peak time. Hence, PV generation will bring severe challenges to the peak-load regulation of the power system.

B. Power losses

When load current flows through the network, losses will be produced in the system form to the existing impedance in each line. Take line 2 (from bus 2 to bus 3) as an example, the active power loss in line 2 along the transmission line in the LV distributed network with and without battery storage are severally represented in Fig. 9 and Fig. 10.

As shown in the Fig. 9, the line loss is better than preciously with PV energy output at noon owing to strong sunlight. However, the variation is steep from trough to peak. With the proper capacity and placement of energy storage used in distributed generation system, the total loss of the network can be reduced. One of the most essential factors which could influence network loss is the load demand. By changing load demand, the line loss will also change.

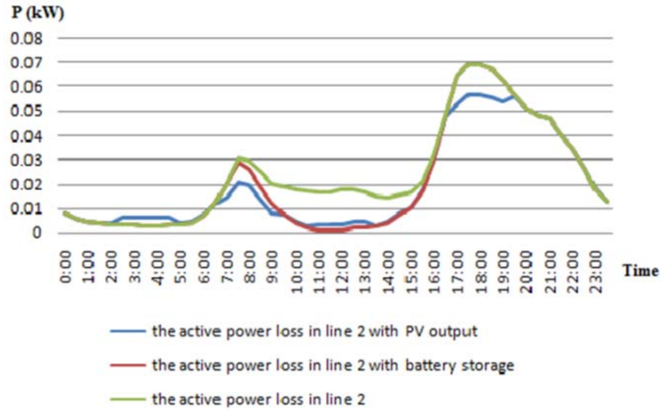

Fig.9 Power loss in line 2 with and without battery storage

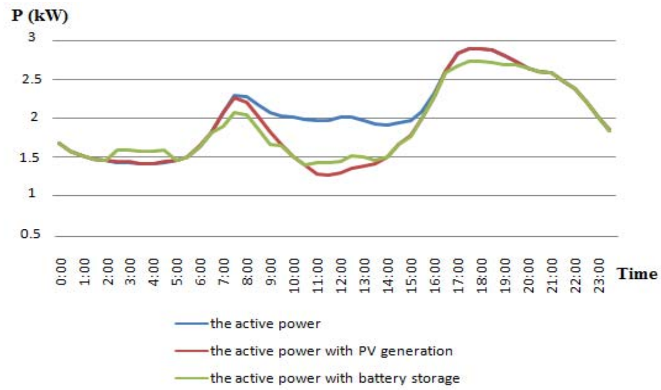

Fig.10 the active power with and without battery storage per household

As noticed in Fig. 10, the original loss in line 2, depicted with the green line, has two distinct spikes under peak demand. In this way, the line loss will be reduced and the capacity will be kept in the limit range as shown in Fig. 13.

If the capacity demand is higher than the rating, it needs to be reinforced. The capacity saving in a year can be calculated by (4):

$$Capacity\ \ savings = \left[0.38\times\left(average\ \ peak\ \ reduction\right)\right] + \left[0.75\times\left(summer\ \ peak\ \ reduction\right)\right] + \left[0.08\times\left(winter\ \ peak\ \ reduction\right)\right] \tag{4}$$

C. Benefit qualification and discussion

The impact of PV generation for one household is insignificant and negligible in the LV radial distribution network. The benefit brought by single battery storage devices is also unremarkable. However, if the numbers of units increase, the influence on voltage levels and line losses could be considerable, and the result of power flow will be more substantial. From the demonstration on one household, the following the results are obtained: Firstly, the load profile is improved. The peak demand is reduced so that the pressure on network caused by residential energy usage will be released. The system is operated more reliably than before because the voltage is controlled to within a reasonable range. After estimating the line loss, the measurement of reducing losses could help the system achieve the maximum benefits on the network.

VII. CONCLUSION

This paper designs a new battery charging and discharging method based on load demand from a typical UK household. Based on the demonstration of a typical LV distributed network, power flow is computed under three conditions. The first one is based on a typical household load profile, and then the network is analysed with PV output. The most important part is to analyse the system with battery backup which could distinctly improve network conditions. From the results, the voltage time-series, line loss and capacity limit on the peak time are better than the regular PV generation system.

The results show that with flatter load profiles than the original ones, the peak demand is clearly reduced with the battery storage strategy. Hence, the voltage and capacity is controlled within a suitable range, the active power loss on the line is reduced.

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